

"Lana'i: An Inside Look at the World's Most Advanced Renewable Energy Micro Grid"

Robert F. Johnson, SunPower
Leo F. Casey, Satcon
Bob Reedy, FSEC
10.12.2009

SUNPOWER



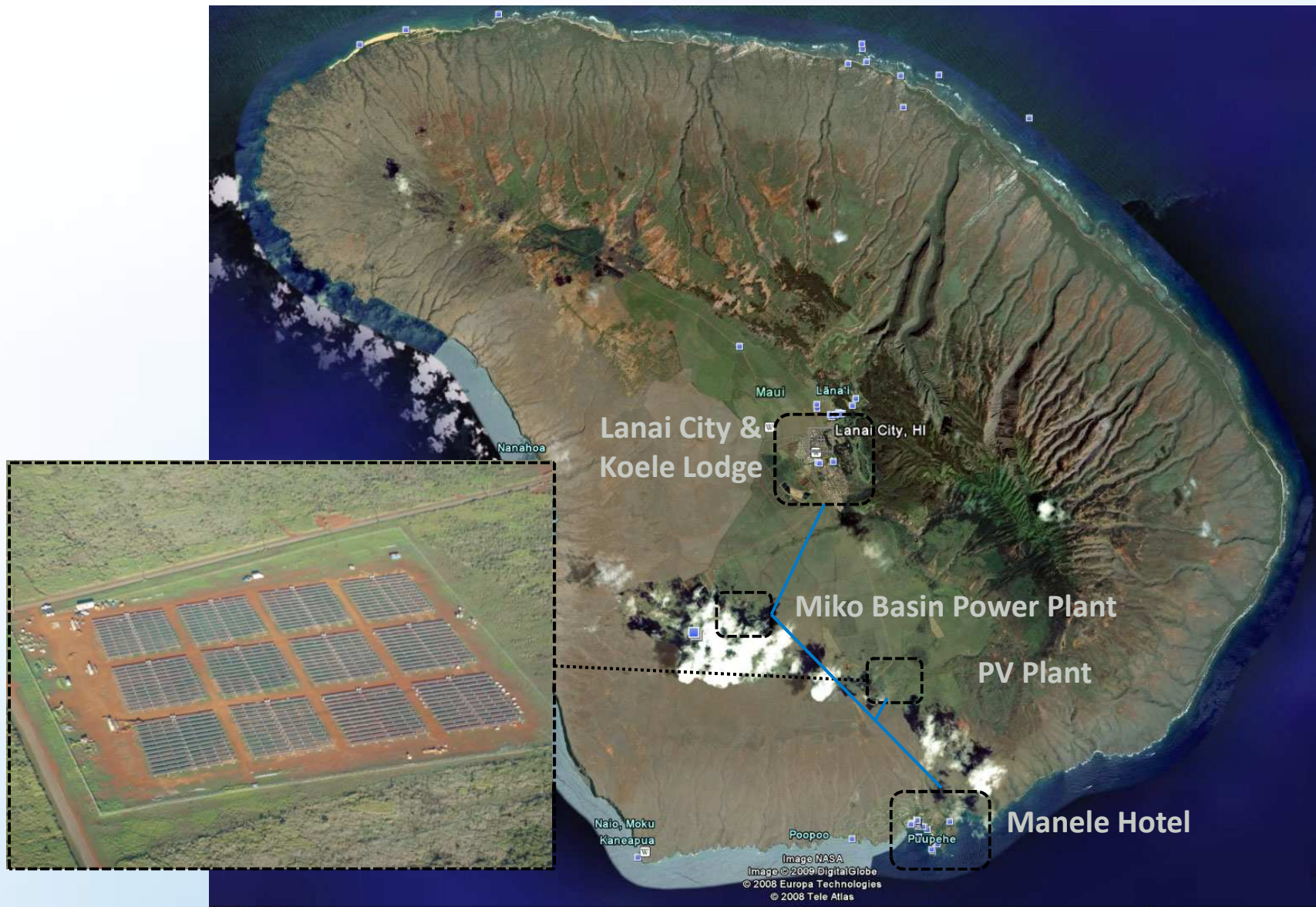
Satcon



Outline

- Robert Johnson- Lana'i PV Power Plant Project Overview
- Robert Johnson- Communications & Controls Implementation
- Leo Casey- Lana'i Grid Stability Challenges, Specialized Solutions
- Bob Reedy – Integration with SEGIS Plans

The Lana'i Electrical Grid



Significant PV penetration reached on Lana'i

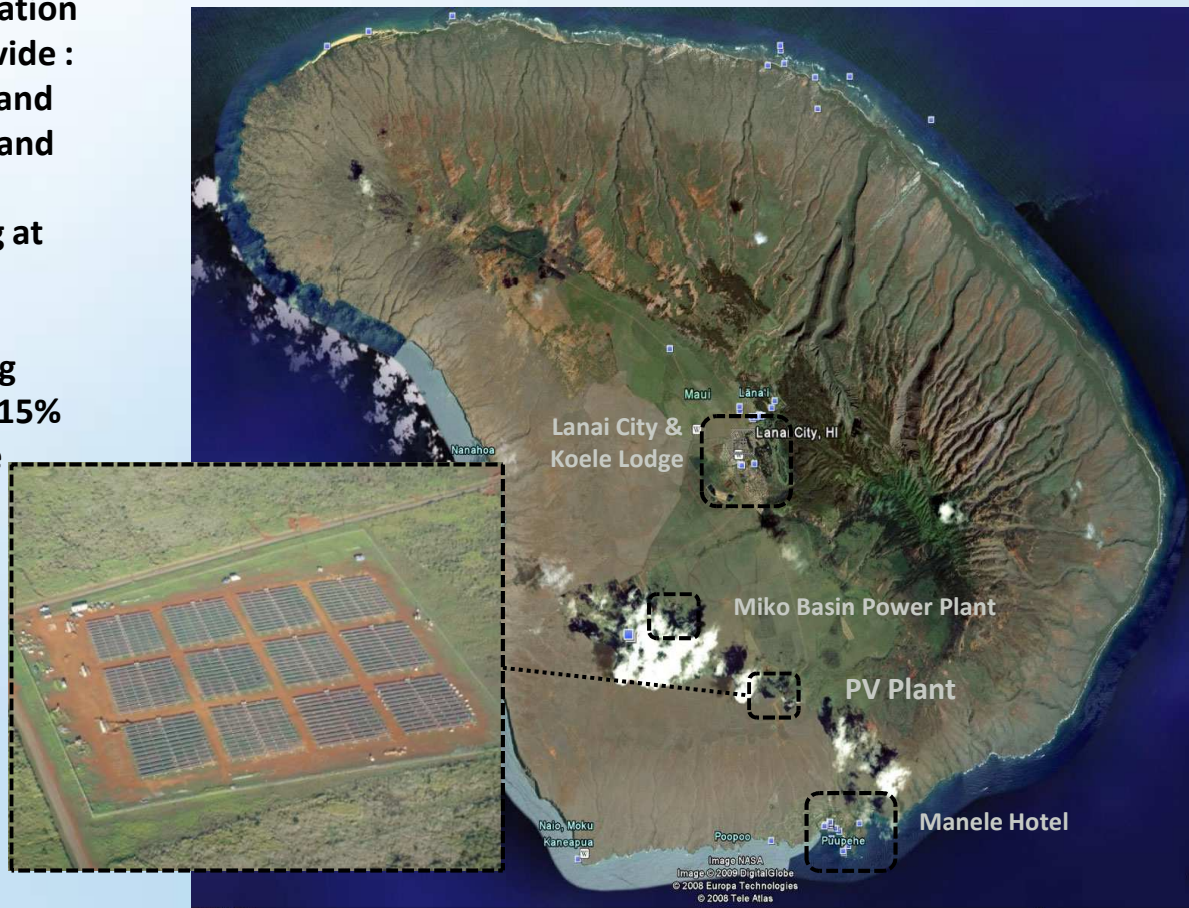
- PV Farm is currently the largest in Hawaii

- The PV system is especially large compared to overall island generation and load and will eventually provide :

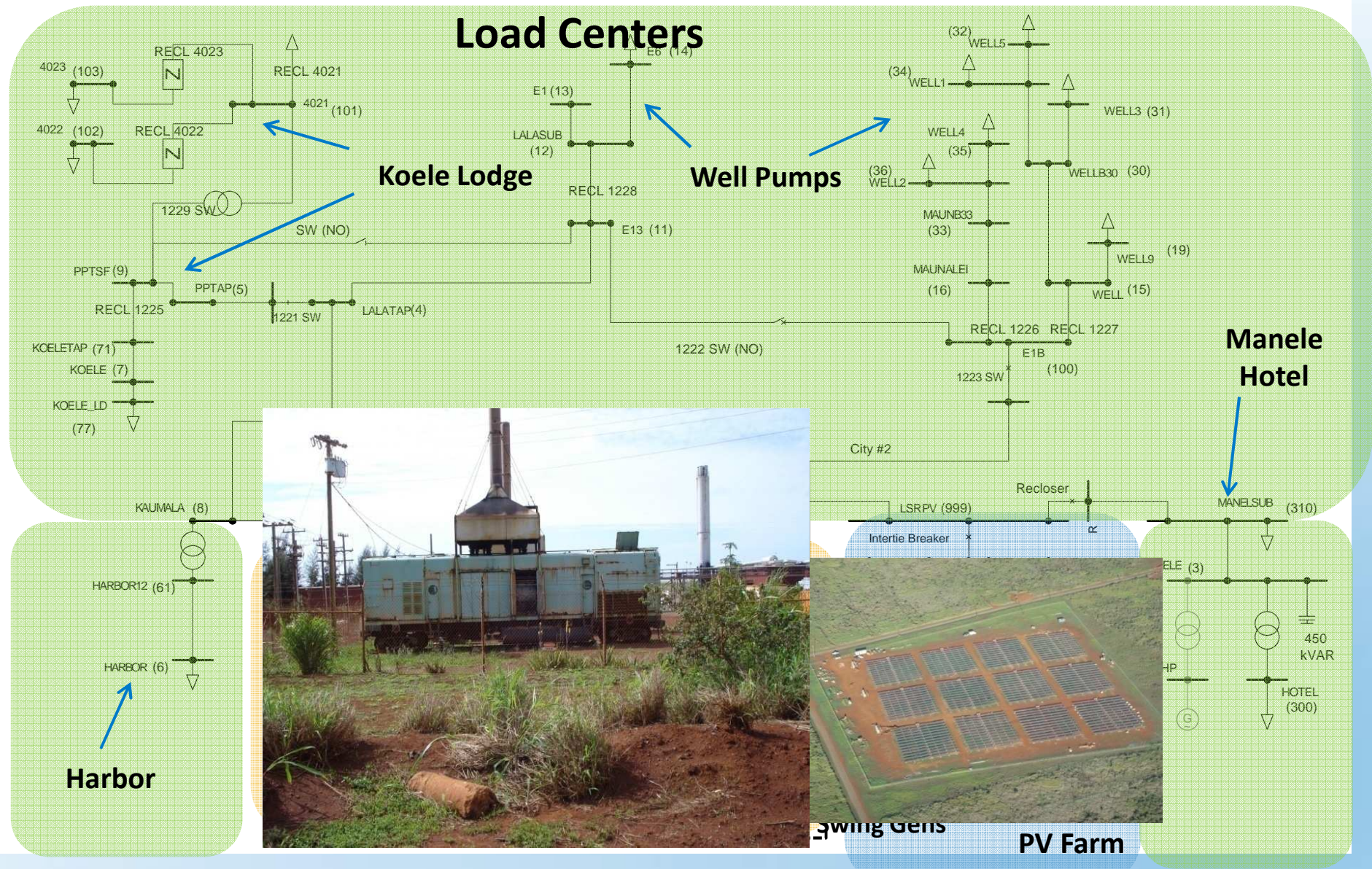
- 10% annual energy demand
- 30% of peak power demand

- PV System currently operating at 600kW

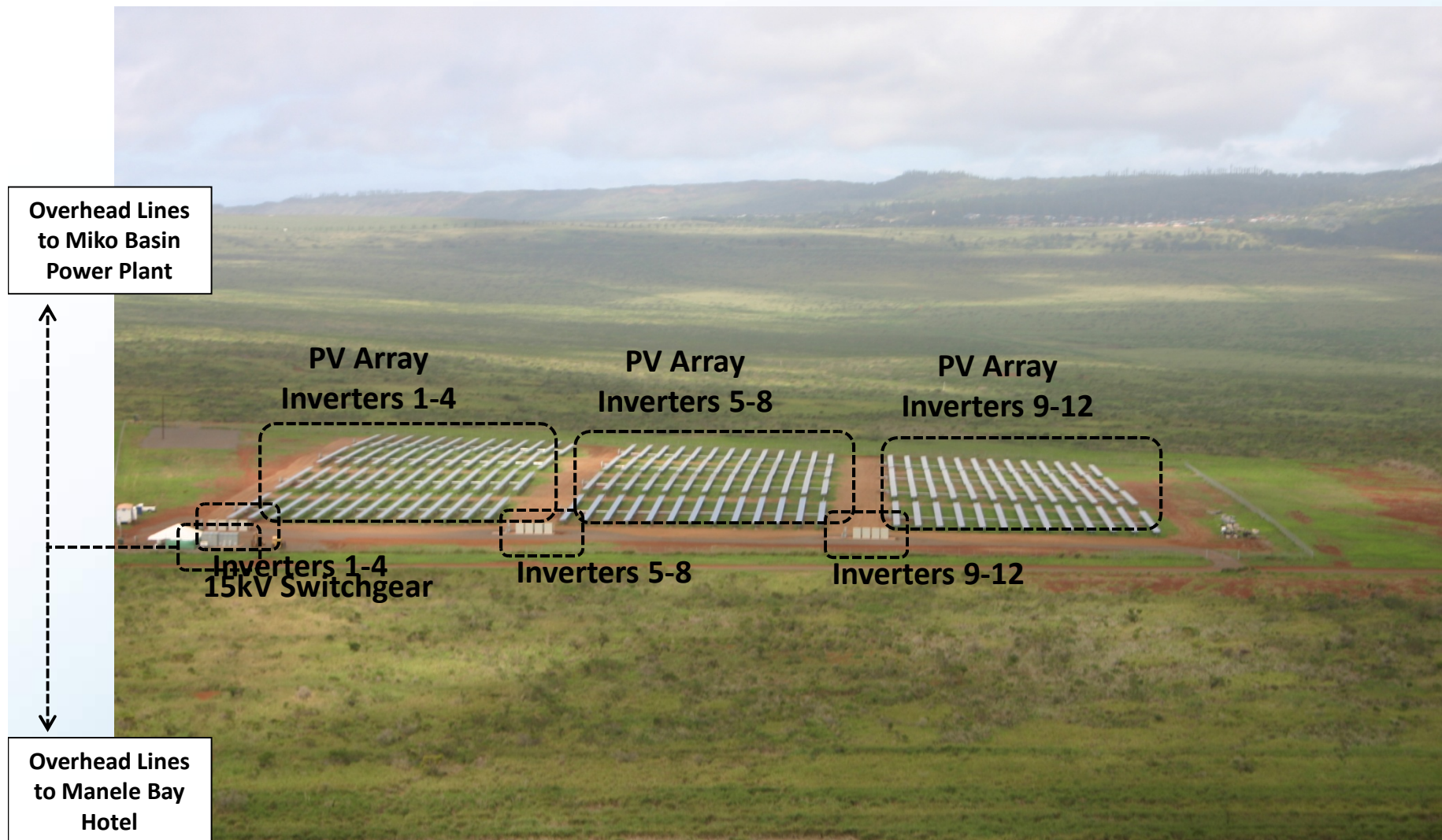
- System is performing withing specifications at approximately 15% penetration without storage



The Small Island System is a “Weak” Grid



The La'Ola PV Farm – System Configuration



Small Island Grid Dynamics Require Enhanced PV Performance

- Lanai's "weak" grid and small centralized generators means grid stability is intimately tied to the PV Farm's performance.
- Impact study conducted by KEMA identifies several Control Features needed to ensure stable operation
 - These features become requirements in the final PPA

➤ **Curtailment Control**

➤ **Power Factor Control**

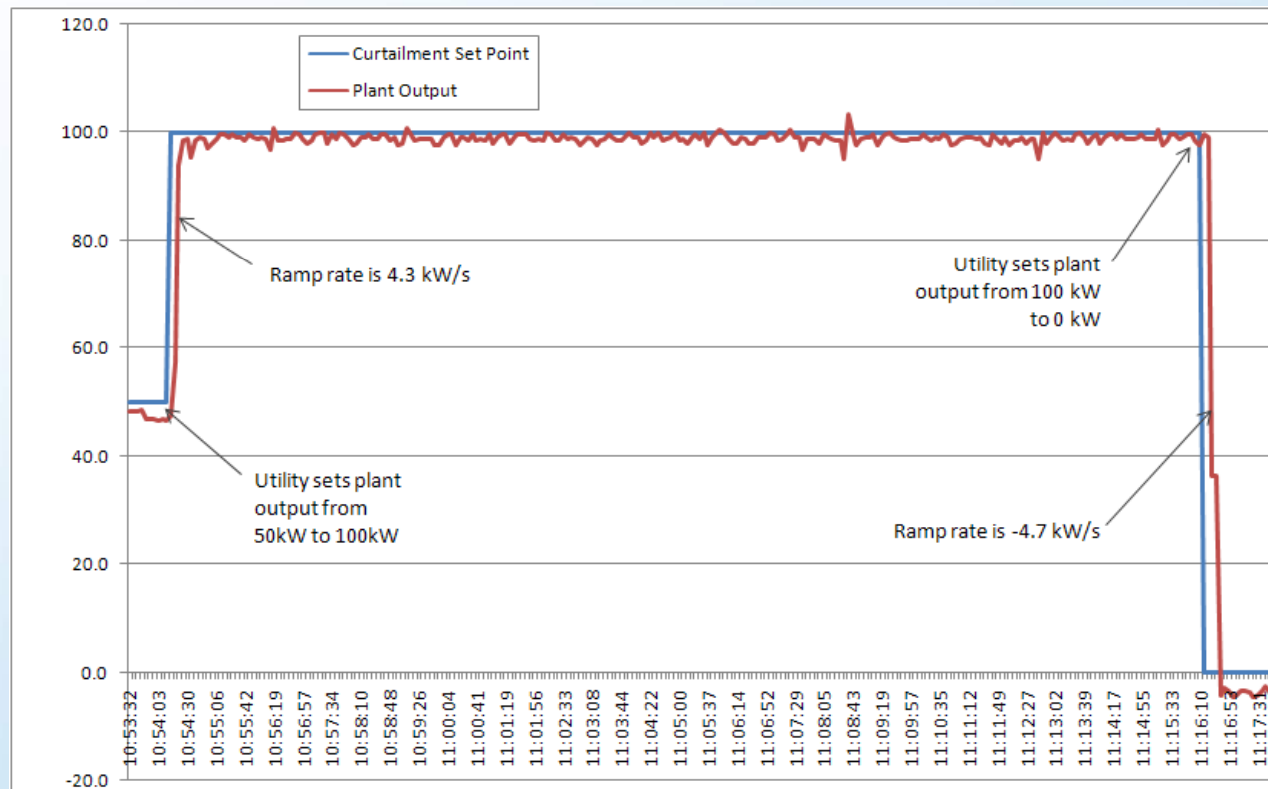
➤ **Ramp Rate Limiting**

➤ **Voltage and Frequency Ride-Through**

Enhanced Performance – Curtailment or Power Limiting

Curtailment Control

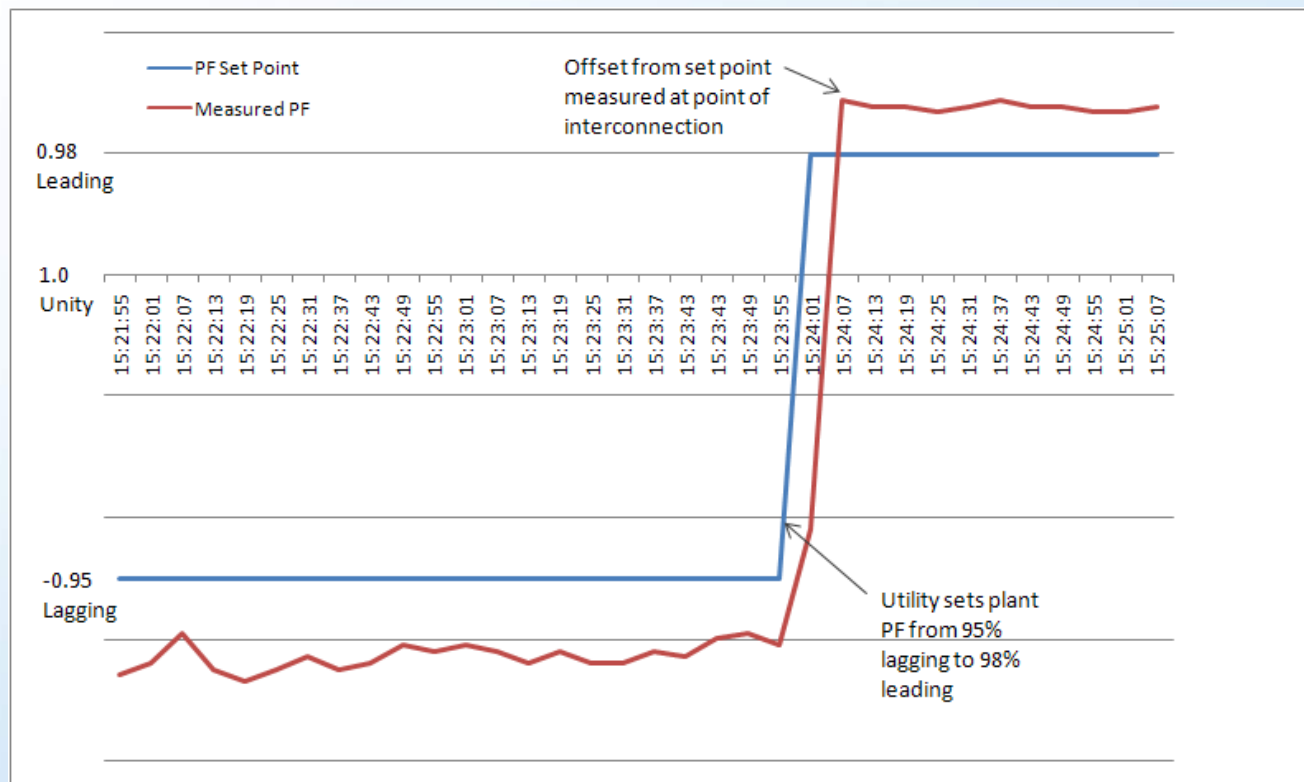
- Utility remotely controls output of PV Farm
- Controllable in relative real-time, and in small increments
- Output is measured at the Point of Common Coupling (POCC)



Enhanced Performance – Power Factor Control

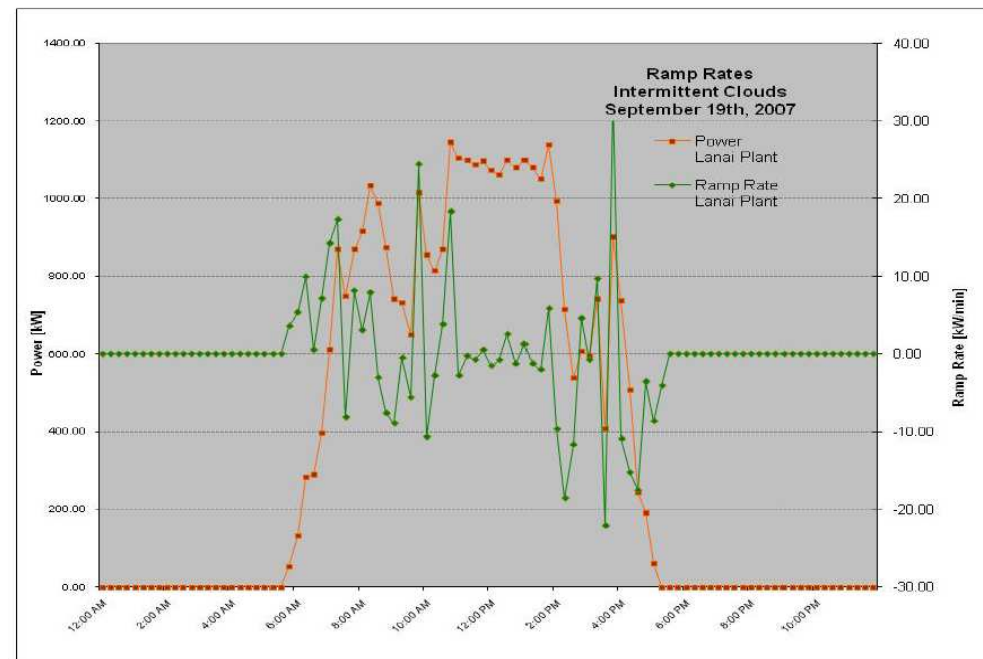
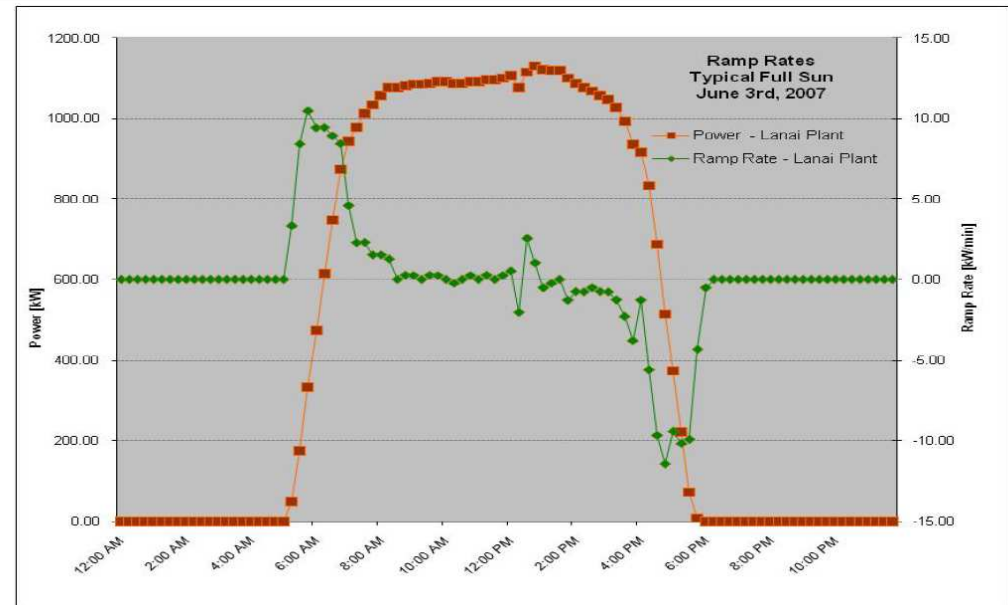
Power Factor Control

- Utility control of power factor from 0.98 Leading to 0.95 Lagging
 - Power Factor measured at the POCC
 - Exporting and Importing Reactive Power at will



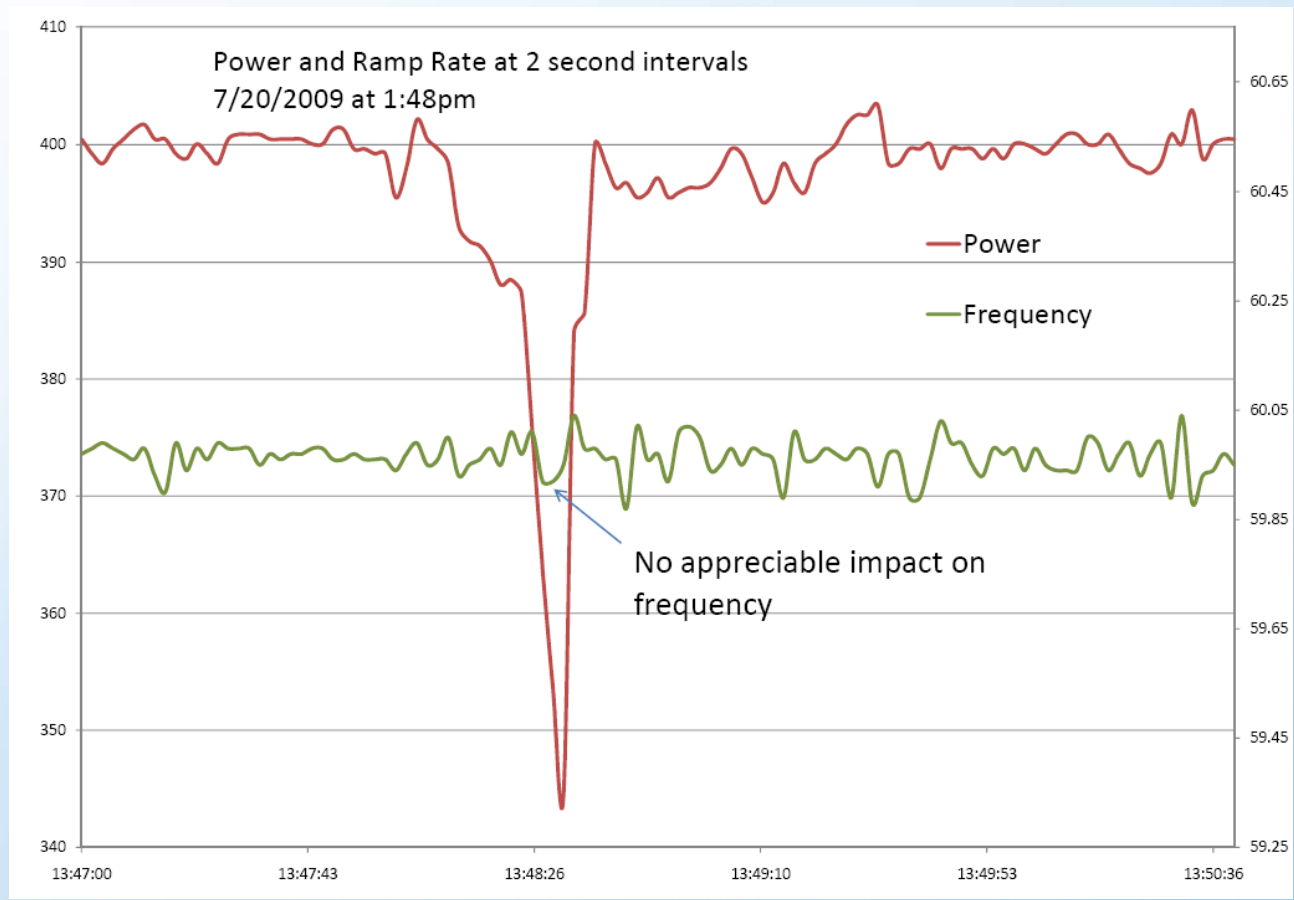
Enhanced Performance - Ramp-Rate Limiting

- The **Variability** of the solar resource means plant output can fluctuate quickly
- Swings in generation and load can cause deviations in frequency in the diesel generators
- PV ramp rates must be limited to 6 kW/s in the morning and evening hours, and 60 kW/s otherwise.



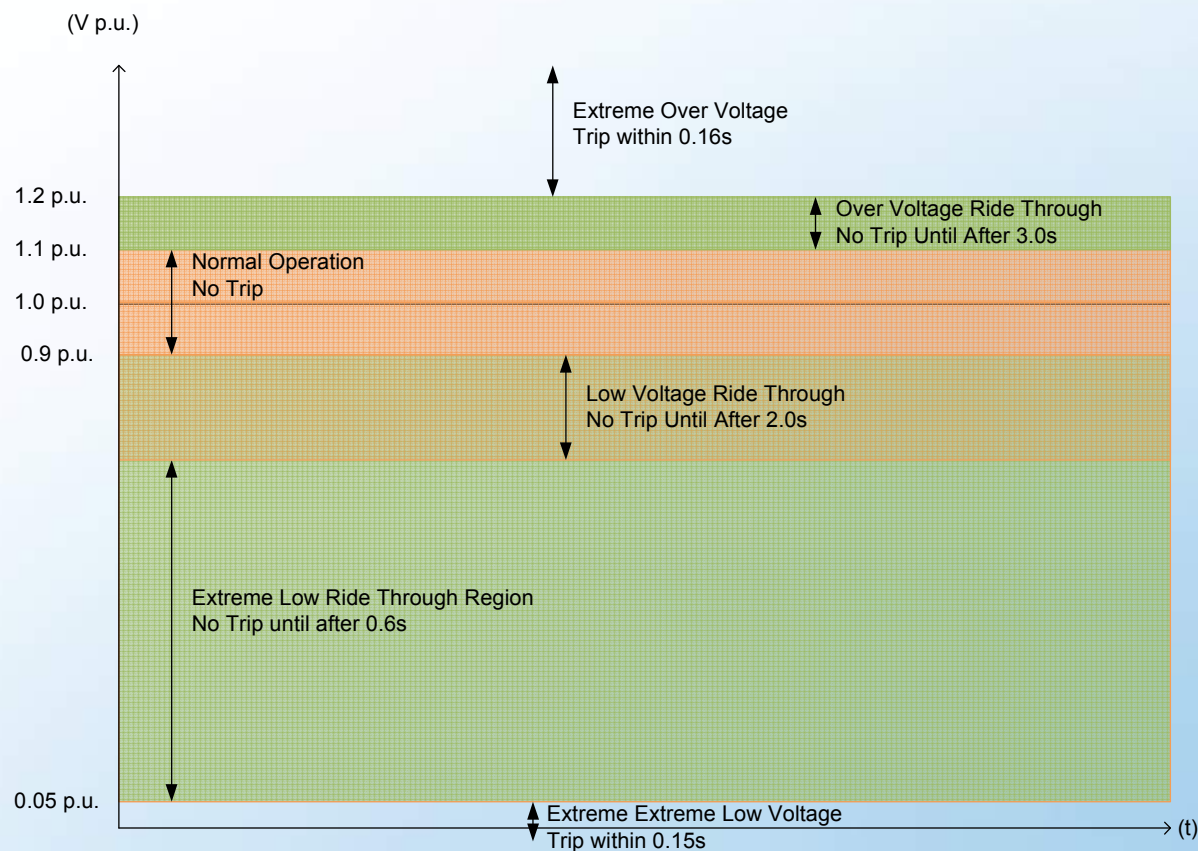
Enhanced Performance - Ramp-Rate Limiting

- Current ramp rates of PV farm have little to no appreciable impact on system frequency



Enhanced Performance – Voltage Ride Through

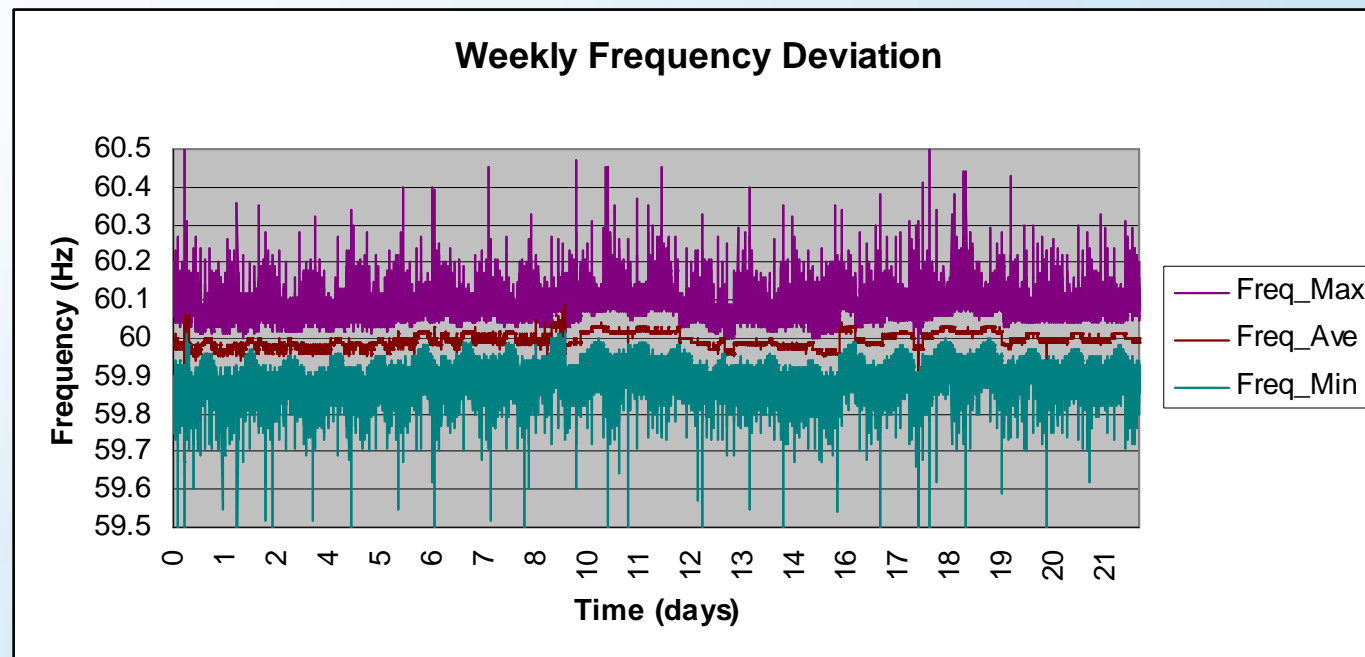
Voltage (at POCC) Condition	Action
$0.9 \text{ p.u.} < V < 1.10 \text{ p.u.}$	Normal Operating Range
$0.70 \text{ p.u.} < V < 0.90 \text{ p.u.}$	no trip until after 2.0 seconds
$0.05 \text{ p.u.} < V < 0.70 \text{ p.u.}$	no trip until after 0.6 seconds
$V < 0.05 \text{ p.u.}$	no trip until after 0.15 seconds
$1.1 \text{ p.u.} < V < 1.2 \text{ p.u.}$	no trip until after 3.0 seconds
$V > 1.2 \text{ p.u.}$	trip within 0.16 seconds



Voltage Operating Window

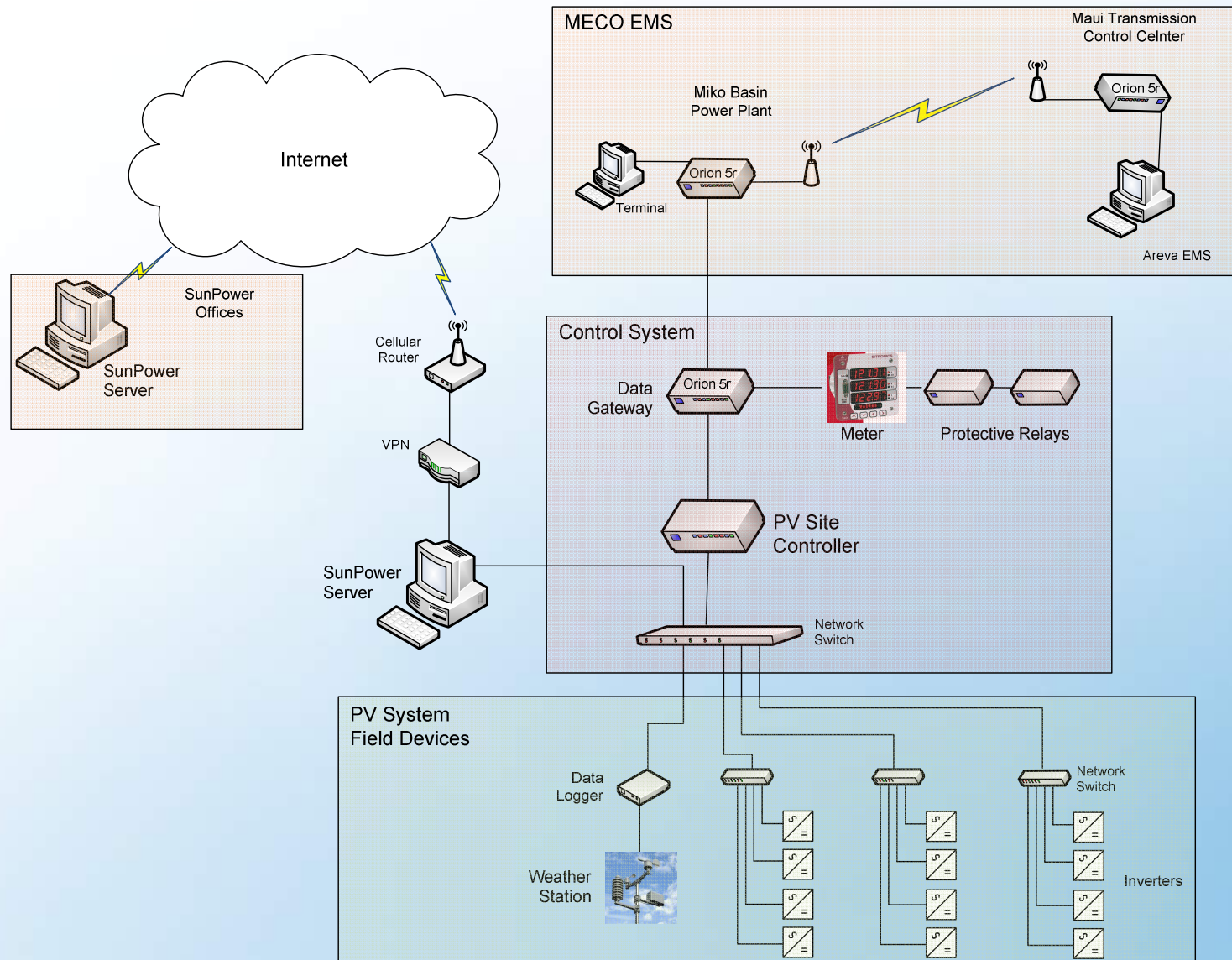
Enhanced Performance— Frequency Ride Through

System Frequency Condition	Action
$57 \text{ Hz} < F < 61 \text{ Hz}$	Normal Operating Range
$F > 65 \text{ Hz}$	trip within 0.16 seconds
$62 \text{ Hz} < F < 65 \text{ Hz}$	no trip until after 2 seconds
$61 \text{ Hz} < F < 62 \text{ Hz}$	no trip until after 6 seconds
$55 \text{ Hz} < F < 57 \text{ Hz}$	No trip, extended ride-through range
$F < 55 \text{ Hz}$	trip within 0.16 seconds



Frequency Operating Window

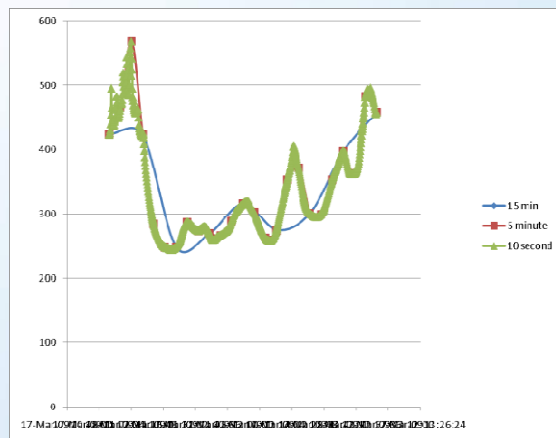
Control System Organization



High Resolution Data Sets & Visualization and Analysis Tools

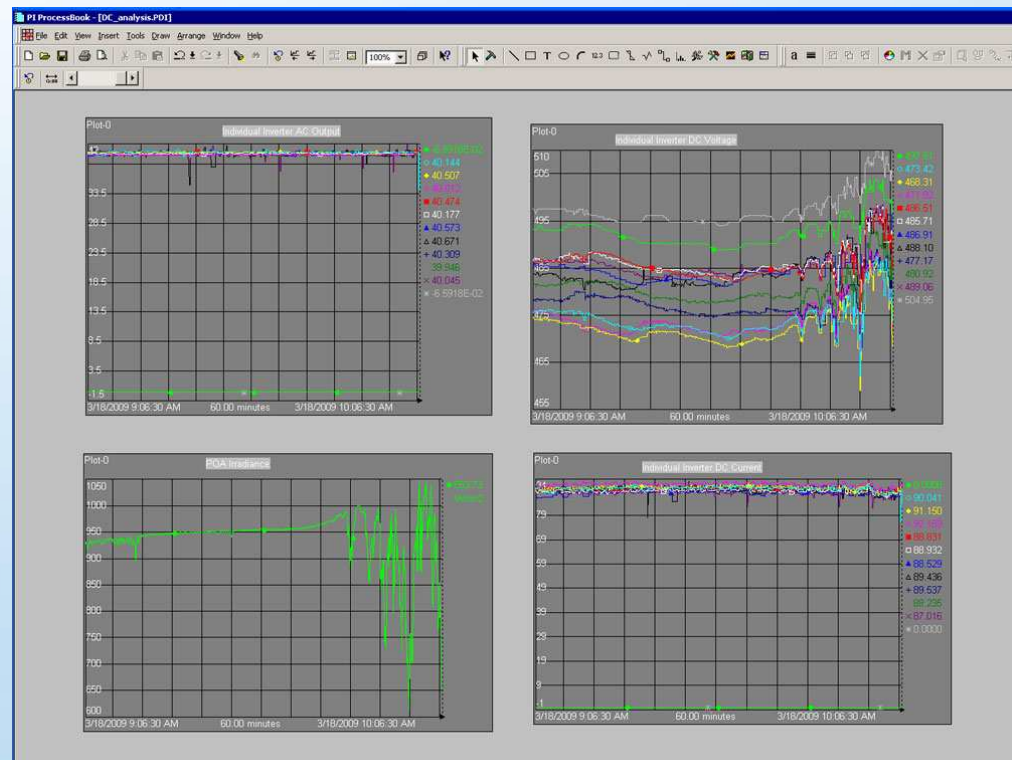
- SunPower has extensive high resolution data sets that are being leveraged to better understand grid integration and performance issues

- SunPower is coordinating with National Labs in analysis efforts



Comparison of 15min, 5 min and 10 sec irradiance data

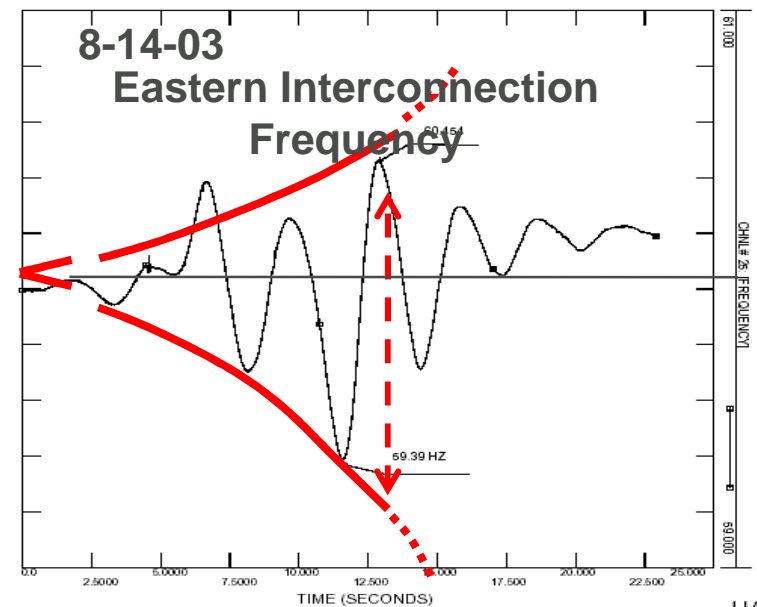
- Visualization tools that enables real-time performance monitoring



2 hour spanning window of Inverter DC performance with Irradiance

Modern Grid Issues

- An age of Increasing Electrification (1.1TW in EI),
 - BUT
 - Energy sources problematic (climate, security!)
 - Grid Power Quality is inadequate to electronic age
 - Slow and Archaic Electromechanical Hardware & Controls
 - **SOME** ANSWERS
 - Efficiencies
 - Renewables
 - Hi-Speed Controls
 - Hi-Speed Devices
 - Reconfiguration
 - TO **SOME** PROBLEMS



Future Grid Vision

- Faster Protection & Control
- More robust
- More renewable
- More efficient
- More DC systems
- **More Electronics
IN ALL LAYERS**
- Higher PQ
- More mGrids
- Improved CF
- More distributed
- Reconfigurable



Barriers

1. Costs

- Panels
- Inverters, BOS
- Integrated Systems
- O&M

2. Controllability

3. Intermittency (Variability)

4. Utility Industry Acceptance/Adoption

- Standards (IEEE1547 – SmartGrid target for reform)
- Familiarity (interconnect studies, protection studies)

Grid Connected Electronics

Grid Energy + Grid Support + Utility Scale



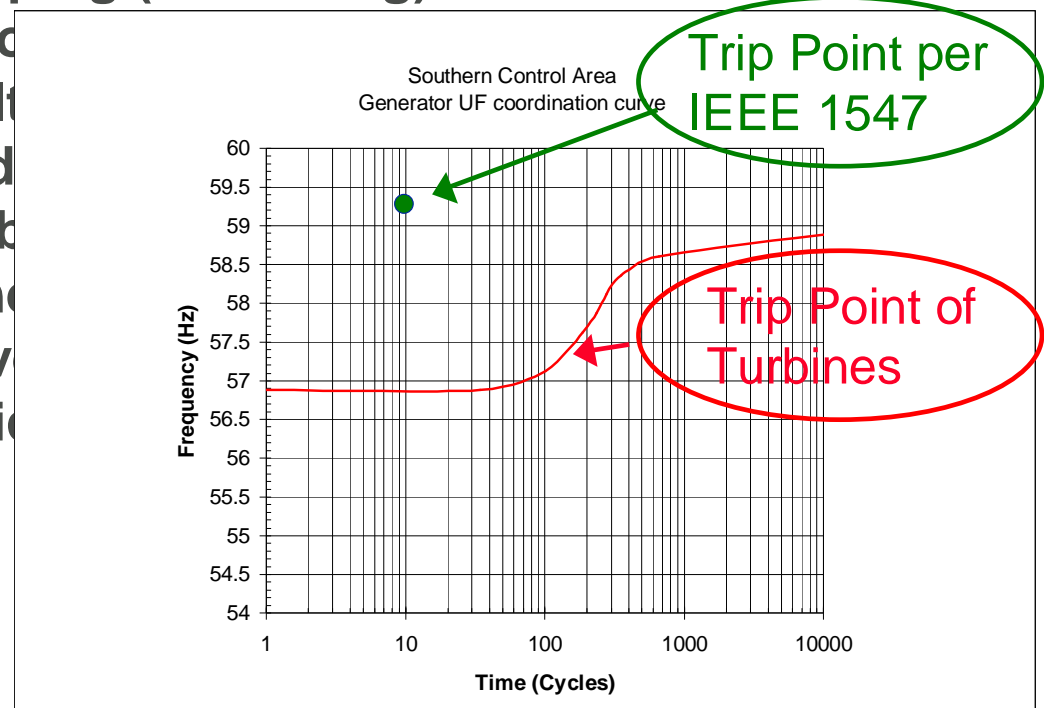
- Instrumentation layer
- Control layer
- Hardware layer



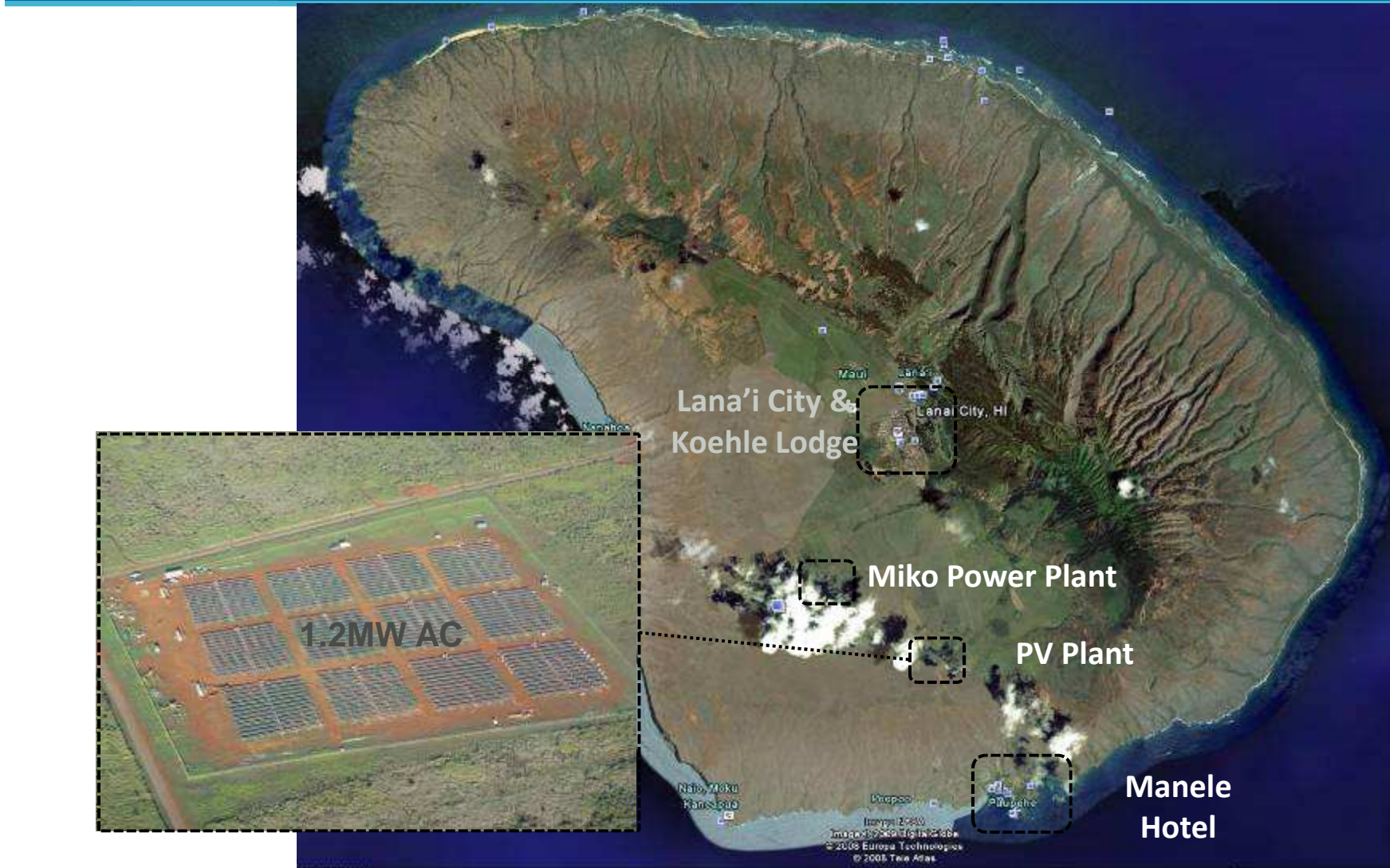
“SmartGrid”
“FutureGrid”

Generation Connected through Electronics – Should be Transformative

- Readily Controllable (remotely)
- Supply Real Power, P , Dynamically
- Reactive power, Q , ($|P + jQ| < S_{INV}$), Dynamically
 - Active Damping (stabilizing)
- Controllable c
 - Fault
 - Rapid
 - Unb
 - Non-line
 - Activ
 - Harmonic



Lana'i PV Power Plant – Modest PV Plant in Small Grid Controlled from Maui



Lessons from Lana'i

- Nominal 4MW load
 - “diesel” grid
 - 1.5MW Solar Farm
- 12 SatCon, 135kW Inverters, 12 SunPower tracking arrays
- 10% of Lana'i annual power demand
- 30% Supply during peak solar hours (4MW)
- **CONCERNS:** potentially destabilizing AND limits of Lana'i grid are extremely wide so non-UL1741 non IEEE1547 inverter required, and under Utility Control
 1. Remote control of Real Power, also termed curtailment
 2. Remote control of Power Factor
 3. Grid disturbance ride-thru capability
 4. Ramp rate limits and control (dP/dt)



Power Limit (Curtailment) & Power Factor Control

- Power Limit involves disabling MPPT routine (“quasi” slew rate possible within Inverter)
- The full range for the power factor command is from 0.71 leading to 0.71 lagging, plus status flag
- Power factor control is realized by keeping real current and reactive current at a fixed ratio determined by the commanded power factor

Power Limit Control	
Communication of power-limit set point	Modbus TCP
Power-limit range	0-135 kW
Power-limit increment size	32.96 W (135/4096)
Ramp-rate limit	6 kW/s
Response time	<5s

Power Factor Control	
Communication of power factor set point	Modbus TCP
Power factor range	0.98 Leading to 0.95 Lagging
Power factor increment size	0.005
Power Factor response time	<5s

- **Implemented**
- **Tested in Certification Lab**
- **Verified at PV-Lana'i**

Ride-Through

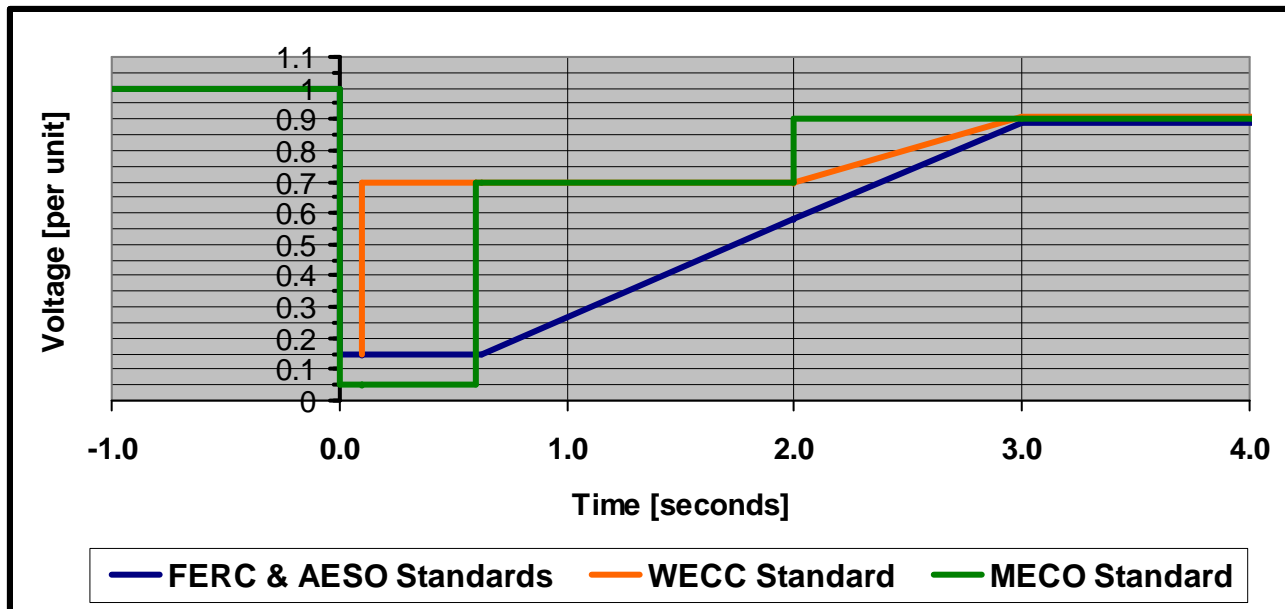
- Traditional Inverters (IEEE1547 & UL1741) operate in narrow range of voltage and frequency and are required by statute to disconnect immediately in the presence of fairly minor deviations.
- The intent here is to operate over a much wider range, and to tolerate fairly rapid dynamics.
- Inverter must operate safely, for extended periods, over the wide voltage and frequency extremes being considered.
- The nominal voltage “V” referenced in the requirements is 12.47 kV at the point of grid interconnect, and 60Hz is the nominal frequency “f” referenced in the table below.
- UPS power is required for control (could be sourced from dc side)
- Implemented, tested (Cert Lab), tested in Microgrid, simulations, observations

Required Ride-Through Capabilities

Grid Frequency	Inverter Response	Grid Voltage	Inverter Response
$65 \text{ Hz} < f$	Inverters must disconnect after 160 milliseconds	$1.20 \text{ pu} < V$	Inverters shall stay online for more than 160 milliseconds
$62 \text{ Hz} \leq f \leq 65 \text{ Hz}$	Inverters may disconnect after 2 seconds	$1.10 \text{ pu} \leq V \leq 1.20 \text{ pu}$	Inverters shall stay online for at more than 3 seconds
$61 \text{ Hz} \leq f < 62 \text{ Hz}$	Inverters may disconnect after 6 seconds	$0.90 \text{ pu} \leq V < 1.10 \text{ pu}$	Inverters shall remain online
$57 \text{ Hz} \leq f < 61 \text{ Hz}$	Inverters will stay online	$0.70 \text{ pu} \leq V < 0.90 \text{ pu}$	Inverters shall stay online for more than 2 seconds
$55 \text{ Hz} \leq f < 57 \text{ Hz}$	Inverters will stay online through this extended ride-through range	$0.05 \text{ pu} \leq V < 0.70 \text{ pu}$	Inverters shall stay online for more than 600 milliseconds
$55 \text{ Hz} > f$	Inverters may initiate disconnection from the grid within 160 milliseconds	$0.05 \text{ pu} > V$	Inverters may initiate disconnection from the grid

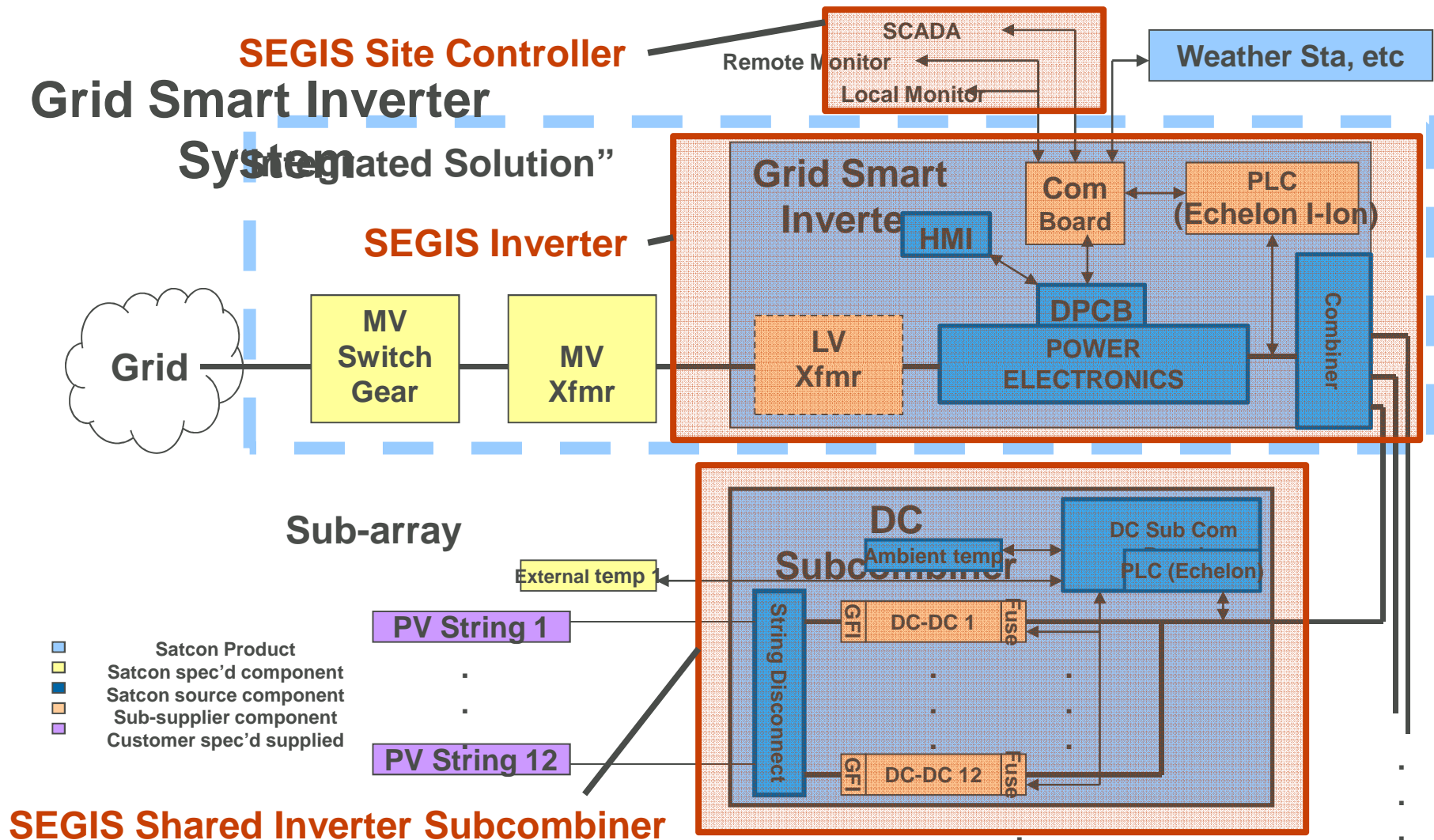
- **Verified quasi statically**
- **Verified dynamically in MicroGrid**

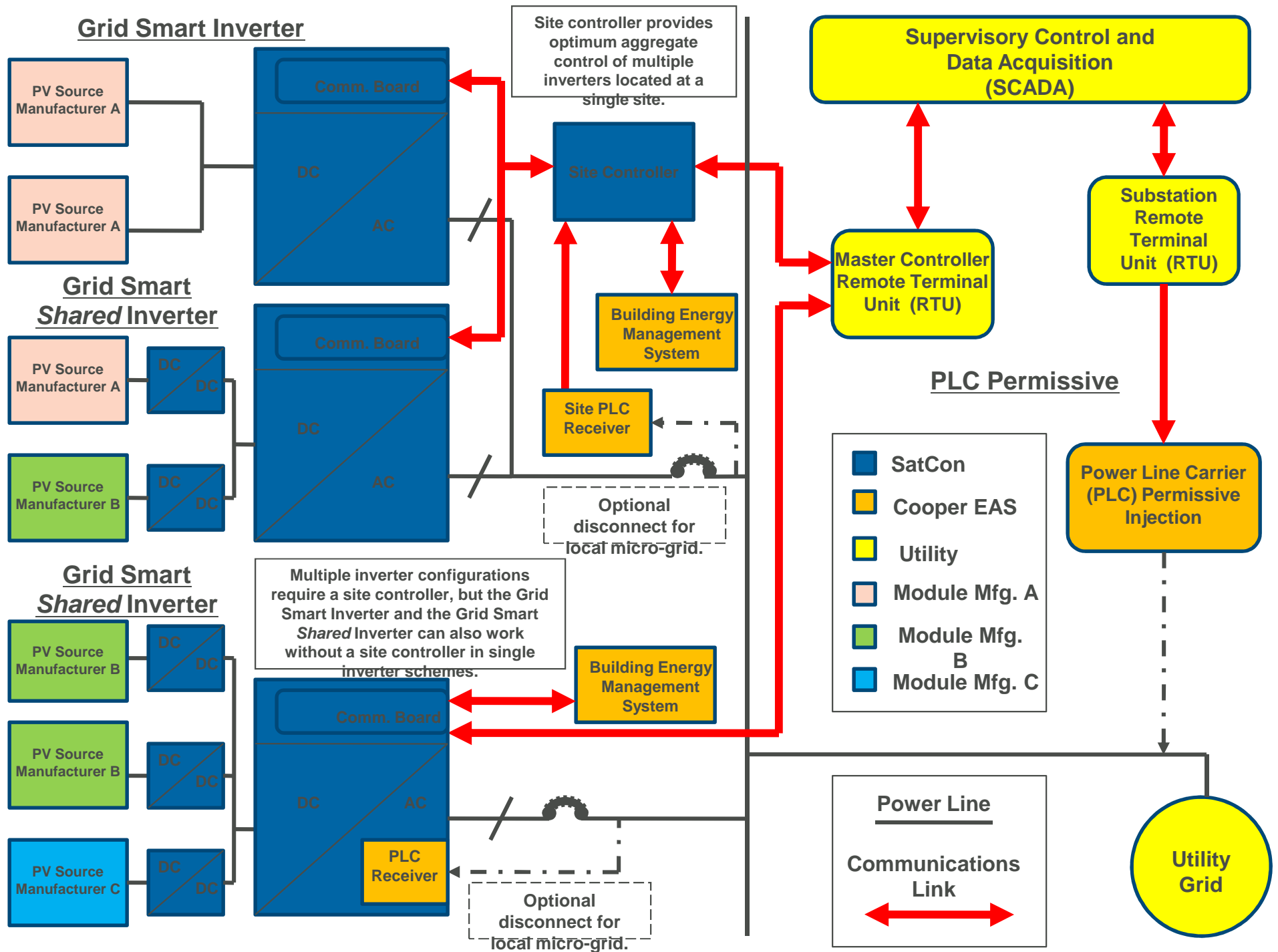
Ride-Through Capabilities



- Focus on LVRT
- Some frequency deviation RT also desired
- Reality is predominance of unbalanced faults
- Flexible MicroGrid is key for testing

SEGIS GSI Block Diagram







Florida Solar Energy Center



Creating Energy Independence Since 1975



- ❖ Research, Applications, Education, Training, Testing
- ❖ Solar Energy Division
- ❖ Building Efficiency Division
- ❖ Advanced Fuels for Energy Division

A Research Institute of the University of Central Florida



FSEC Team SEGIS

Goal: “Walk Like a Duck”



**PV in Aggregate, Behaving Like
Conventional Utility Generation--
& Then Some**



FSEC Team SEGIS: Innovations



- ❖ Utility Control of Islanding
 - Maintain DG when needed most
- ❖ Utility Control of Inverter VAR Generation
 - Use of DG asset in a new way
- ❖ Shared Inverter Designs for Complex Sites
 - Cul-de-Sac Plant, Linear PV Farm, Weird Roofs





FSEC Team SEGIS: Critical Features



- ❖ Enhanced island protection
- ❖ Utility control of online/offline status
- ❖ PV generation ride-through of grid disturbances
- ❖ Fast & Dispatchable VAR Support
- ❖ Peak-shifting & anytime-emergency peak generation with energy storage & BEMS





FSEC Team SEGIS: Enhanced Features



- ❖ Stabilization of Mini/Micro Grids (Island)
- ❖ Harmonic Cancellation
- ❖ Deliberate Phase Unbalance
- ❖ Prognostics and Diagnostics
- ❖ Real-time phase balance of feeder circuits
- ❖ Enhanced transient response (H Constant)
- ❖ Oscillation Damping
- ❖ Spinning & Ready Reserve



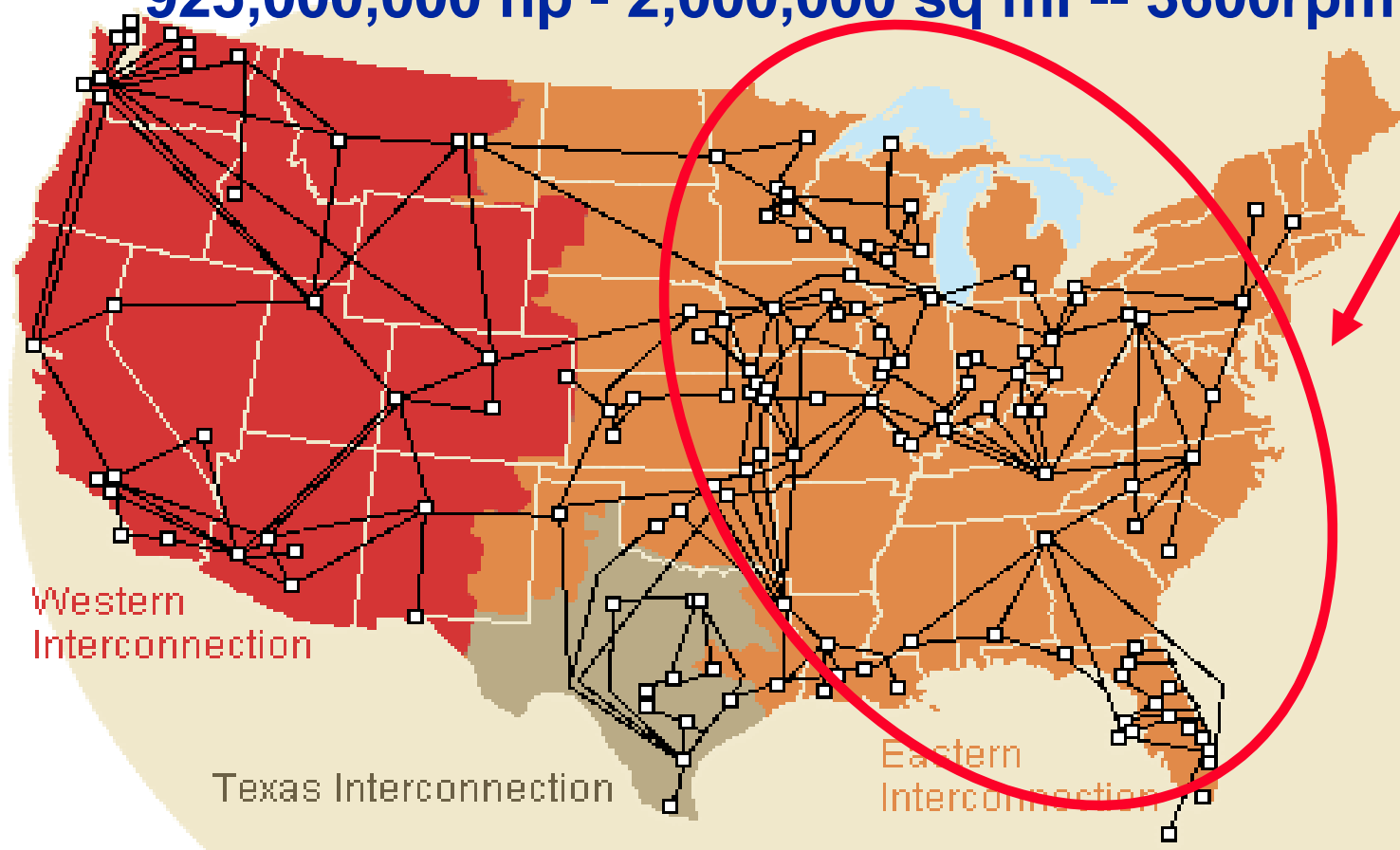


*The Really **BIG ISLAND:***



Eastern Interconnect-- “the World’s Biggest Machine”

925,000,000 hp - 2,000,000 sq mi -- 3600rpm



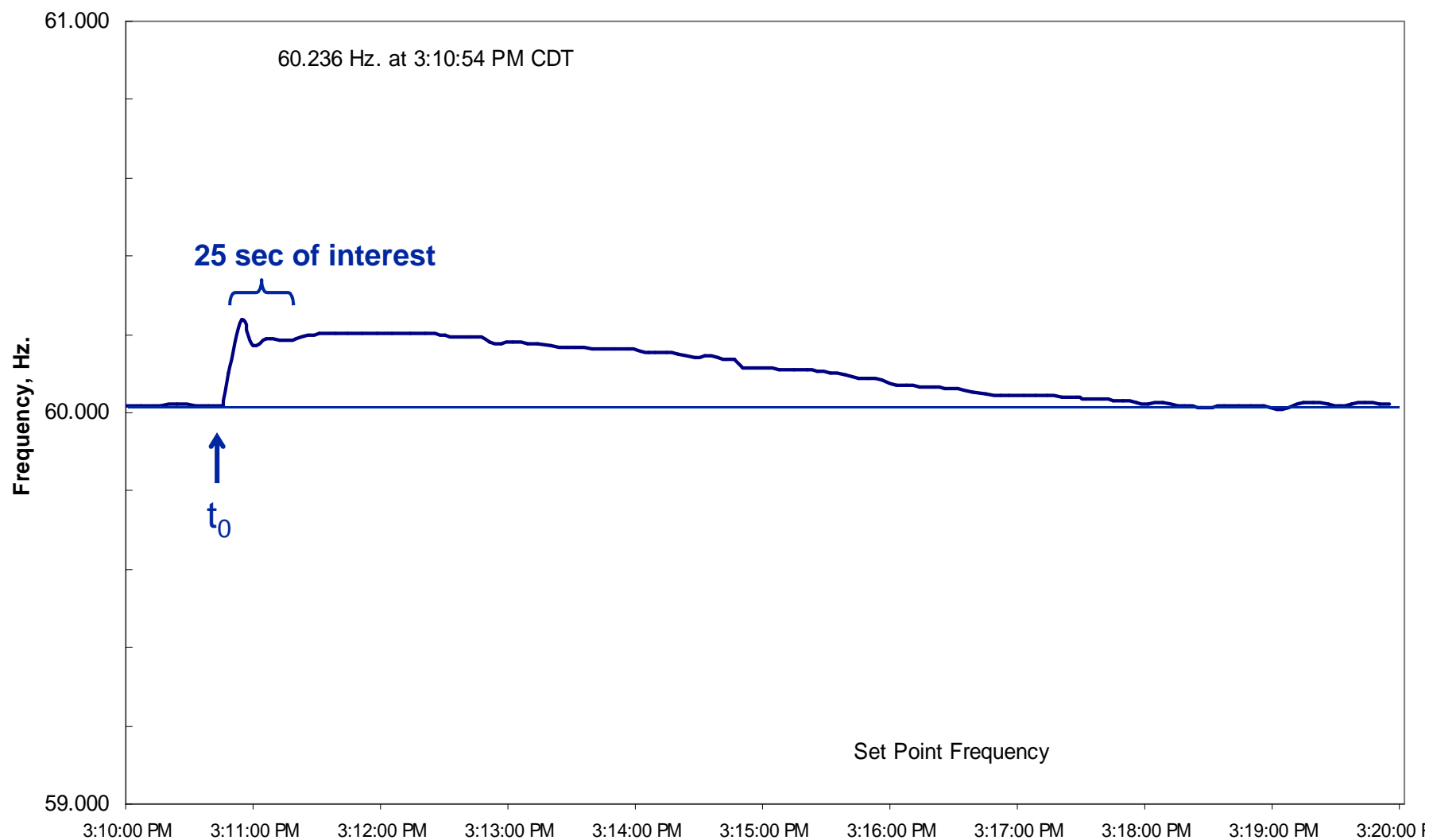


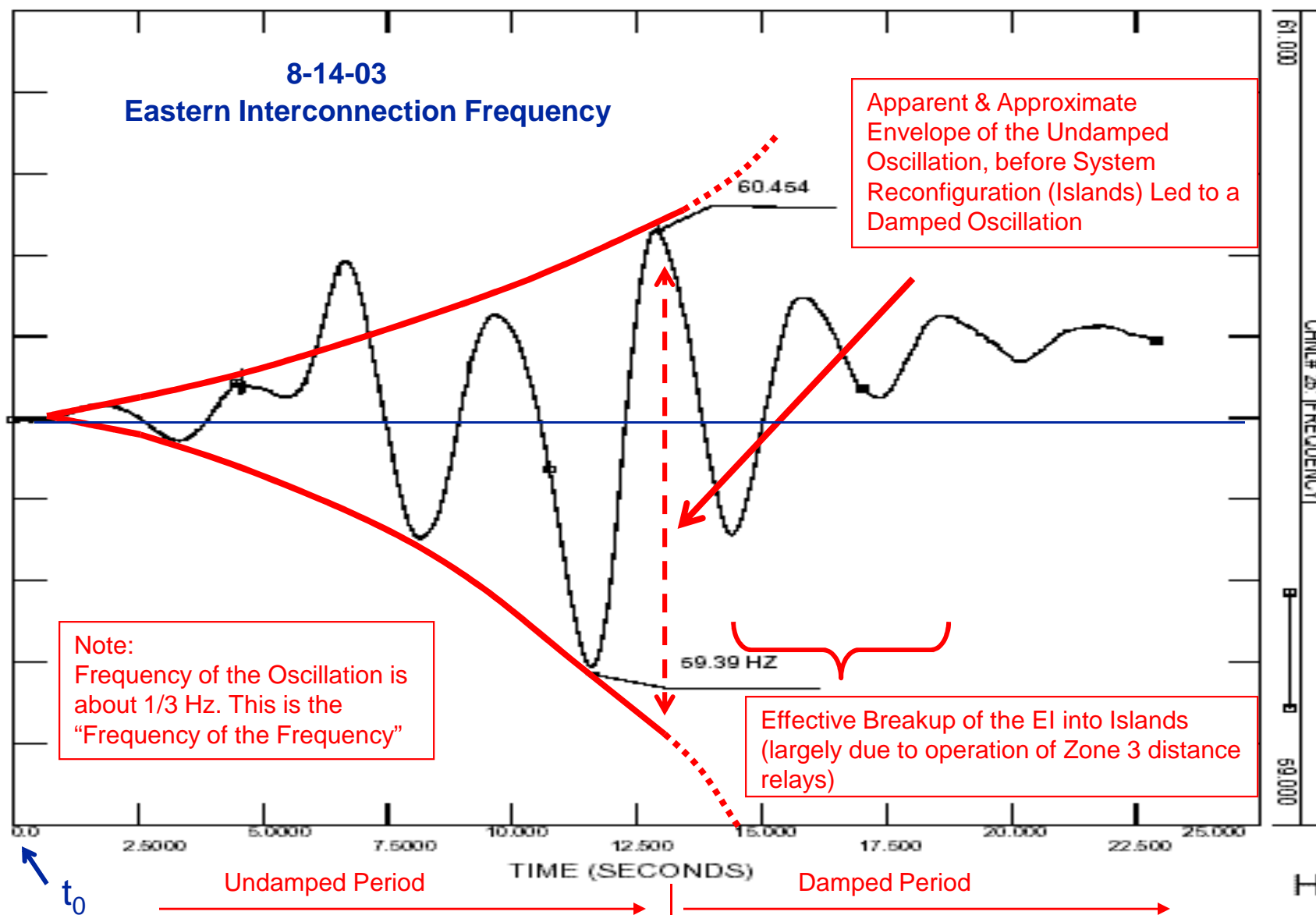
Frequency Excursions

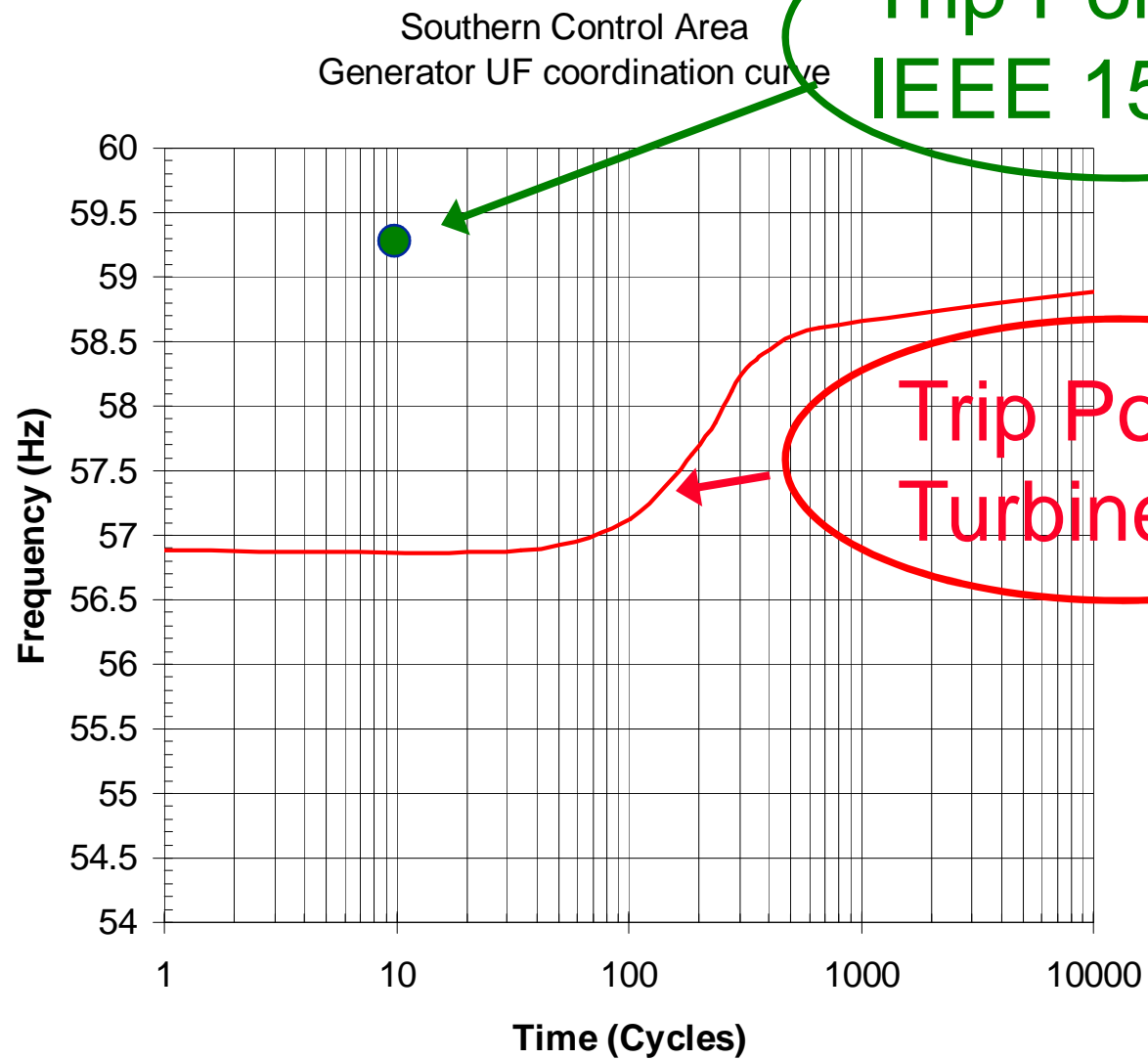


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Eastern Interconnection Frequency

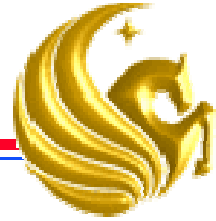




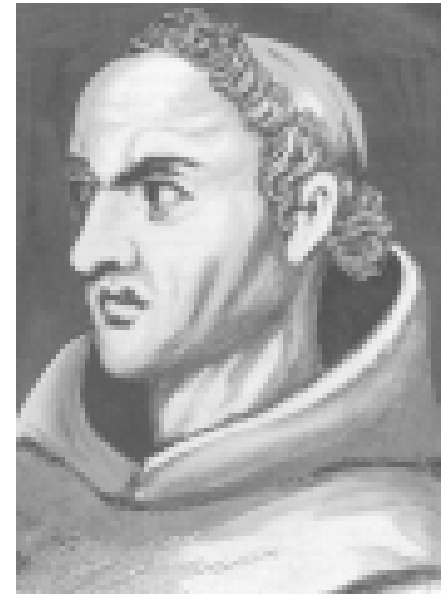




“Anti-Anti” Islanding Back to Basics:



- ❖ Control Areas Use Permissive PLCC to Maintain Generation During Disturbances
 - No Freq Push issues with high penetration
 - Certainty with down lines
 - Provides Control Area Shutdown Capability during Over Generation events



*William of Ockham
b. 1285 Surrey, England*

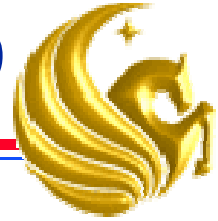


Old View – Island BAD





New View – Island GOOD



Thank you.

Contact:

SUNPOWER

✓ Robert Johnson

✓ (510) 260-8373

✓ Robert.Johnson@sunpowercorp.com

Contact:



✓ Bob Reedy

✓ (321) 638-1470

✓ reedy@fsec.ucf.edu



Contact:



Satcon

Clean power.

✓ Leo Casey

✓ (617) 897-2435

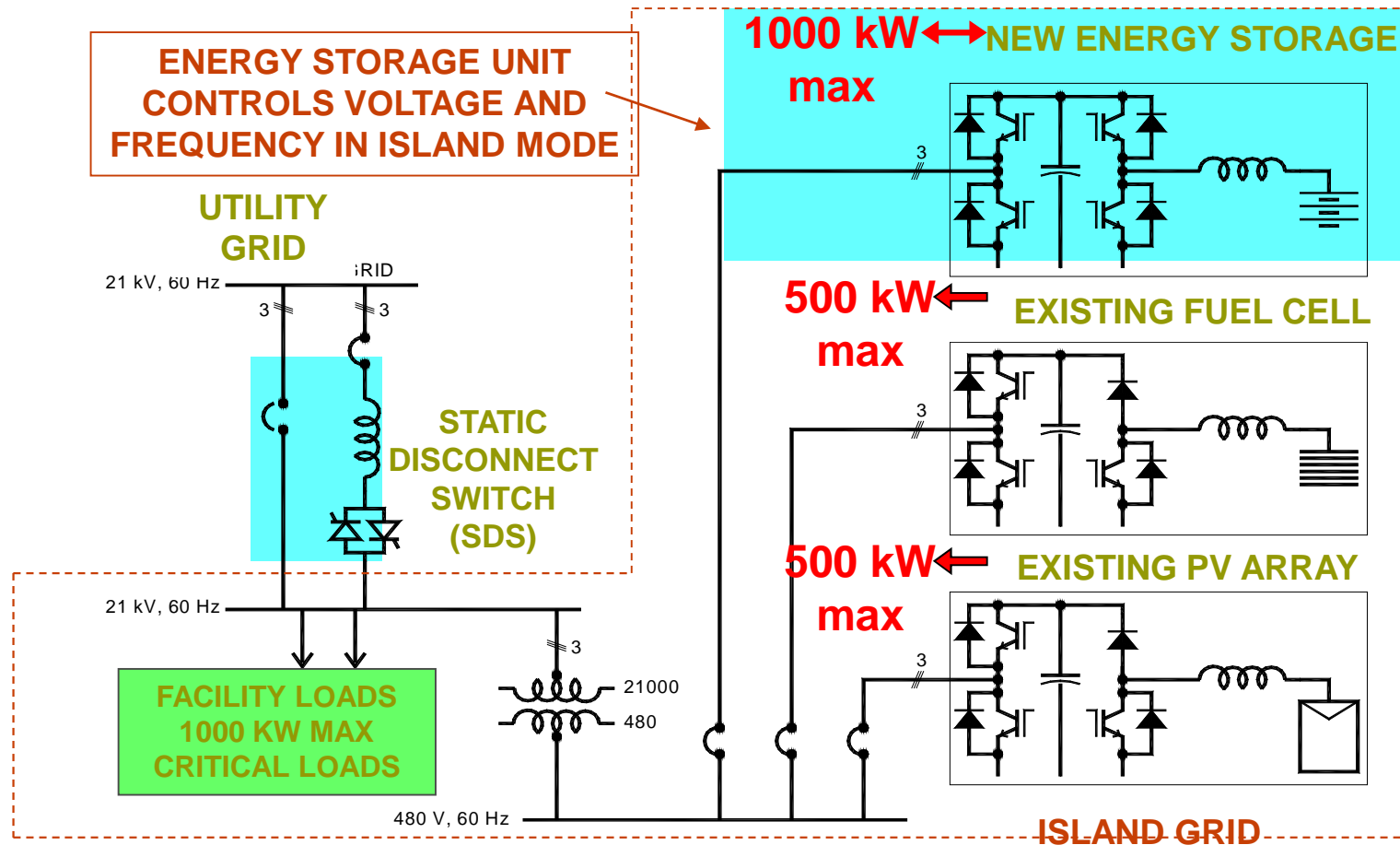
✓ Leo.Casey@SatCon.com



BACKUP SLIDES



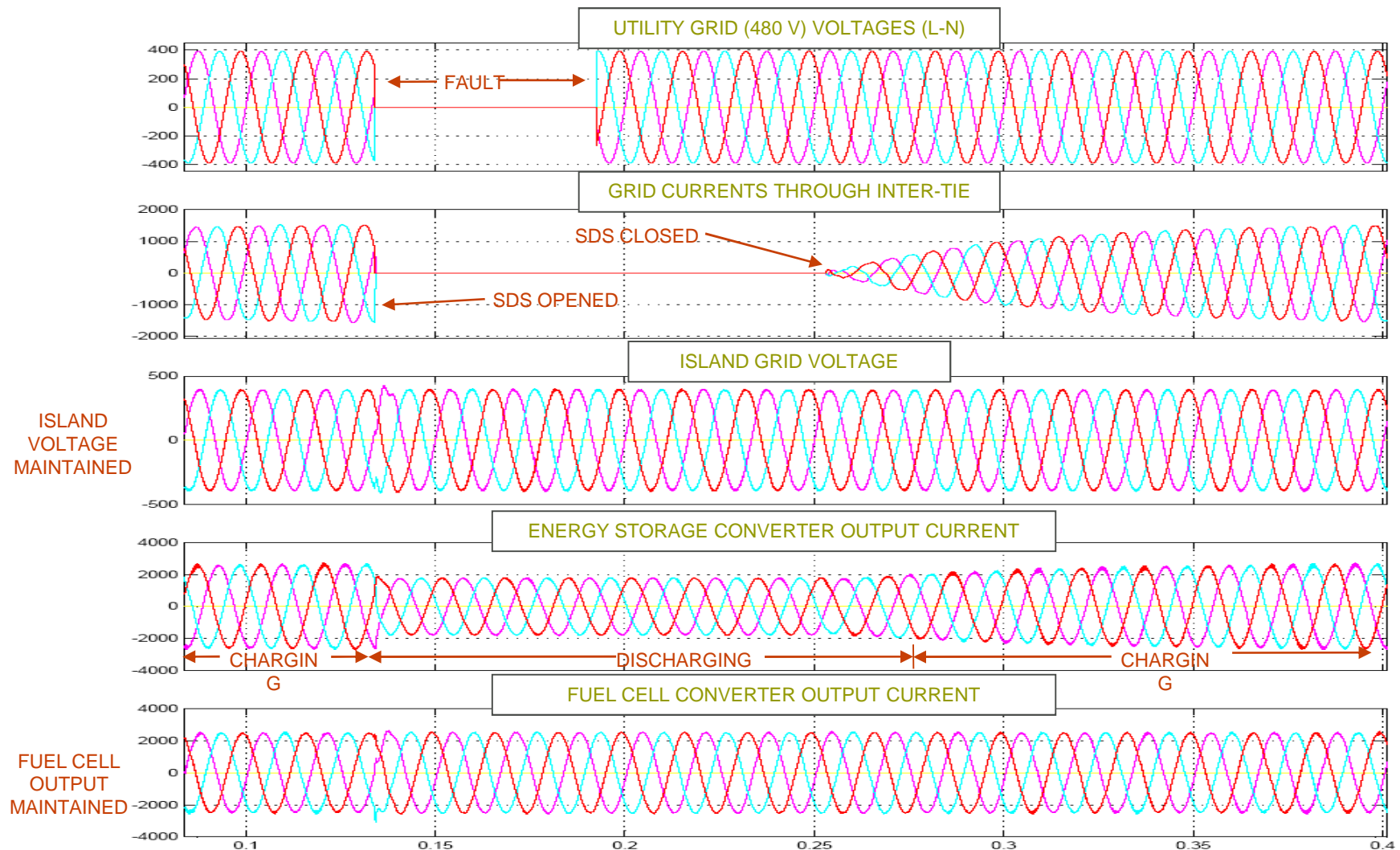
MicroGrids – “ACCESS” & SDS Enable UPS-PQ



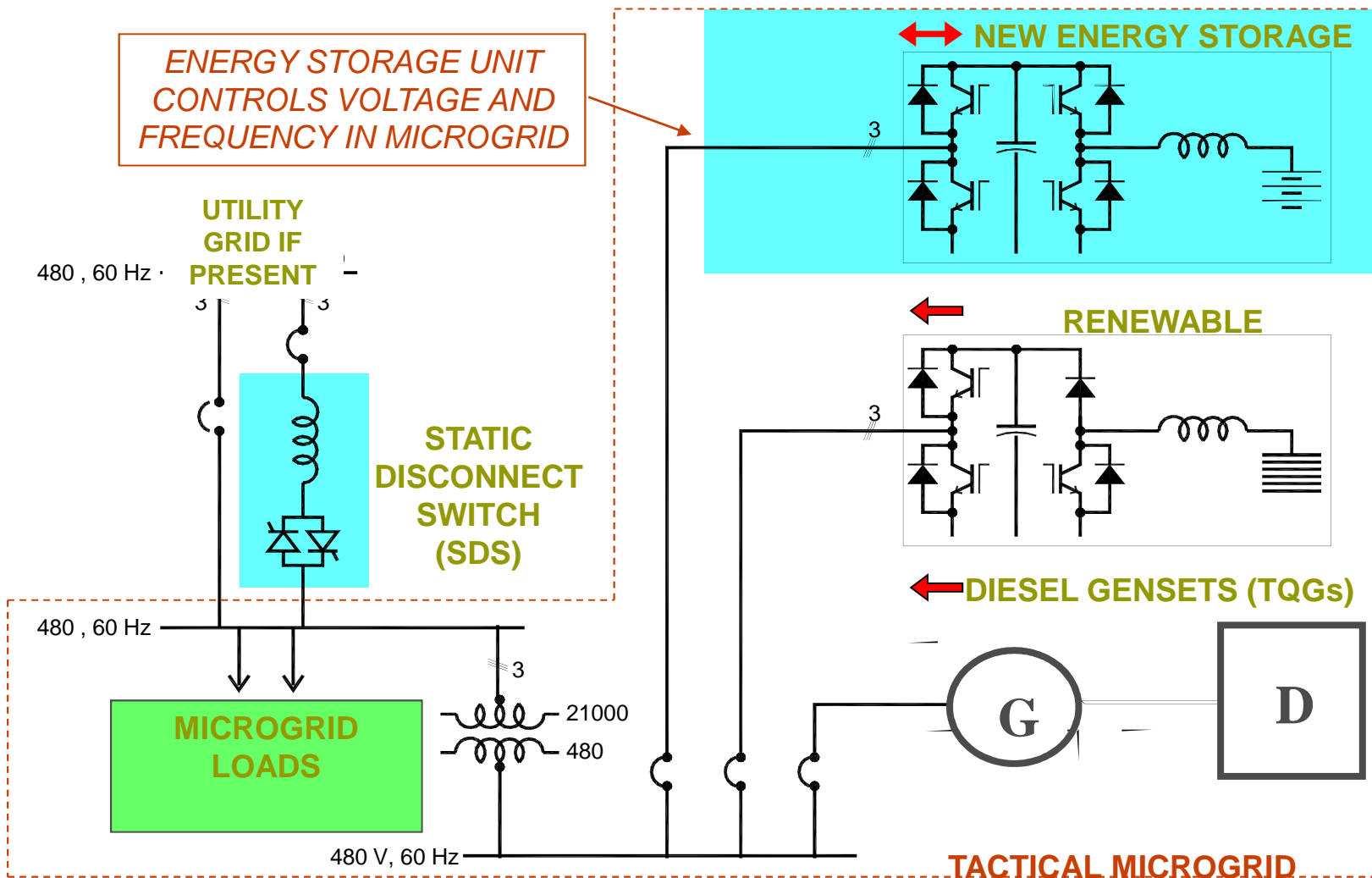
- Renewables plus back-up generation plus storage plus SDS
- UPS quality power

Simulated 3-Phase Fault on Utility Grid

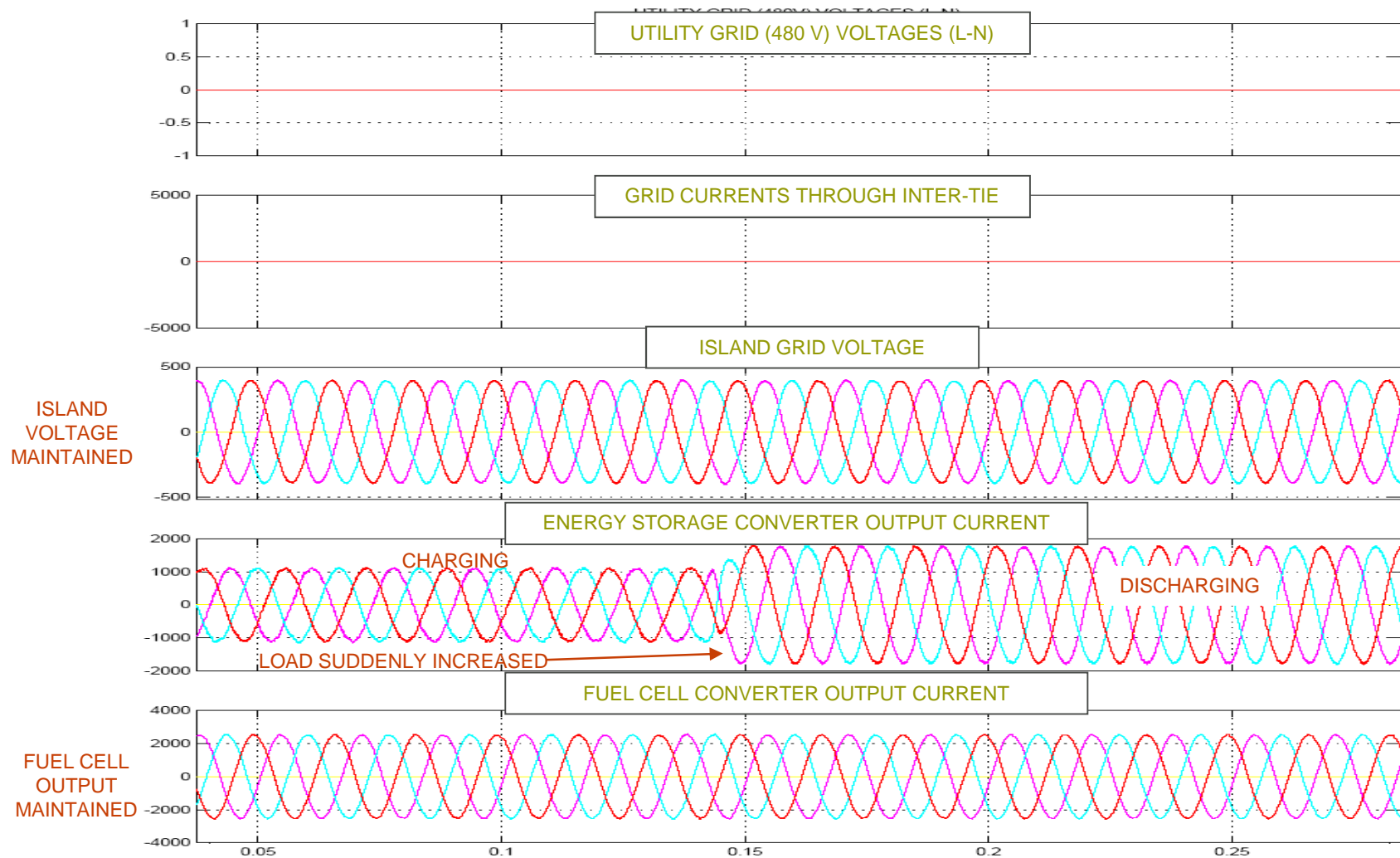
2.2 MVA, 0.8 P.F. Constant Load on MicroGrid



Utility Grid Connection optional – Tactical Micro Grid



Simulated Operation in Island Mode -Load Suddenly Increased (1.1 to 2.2 MVA, 0.8 P.F.)



Lanai



True “Island” Grid

Palawai Basin - 10 Acre Site

**Advanced Inverter Features implemented
under Utility Contrtl**